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MUON FLUENCE MEASUREMENTS AT 800 GeV

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INTRODUCTION

Muon fluence (muons-cm^{-2}) was measured downstream of enclosure PW8 at three locations along the extension of the PW beamline during the 1984 800-GeV accelerator run. The main goal of these measurements was to determine muon dose-equivalent at various Fermilab locations, and to obtain an estimate of the yearly off-site radiation exposure to the general population due to accelerator-produced muons. The contribution from the PW beamline was investigated because the targeted primary proton beam intensity was consistently higher than for other beamlines. More extensive but similar measurements have been reported by Cossairt[1] for 350 and 400 GeV operation.

EXPERIMENTAL TECHNIQUE

The measurements were performed with the Mobile Environmental Radiation Lab (MERL). This vehicle is equipped with a pair of 0.64 cm thick plastic scintillator paddles (20.3 cm x 20.3 cm) seperated by about 15 cm, with a 2.54 cm thick aluminum plate located in the gap. Standard electronics modules were used to record on scalers both singles and coincidence events from the two detectors. A microwave telemetry system provided signals to gate the scalers on during both beam-on and beam-off time periods in synchronization with the accelerator cycle. The spill length was about 20 sec. long for an accelerator cycle of 60 sec. during these measurements.

The three locations at which measurements were made are described in Table 1. Data was collected by moving the detectors along a line approximately normal to the muon flight paths. At each position along a scan detector counts were recorded for at least two, and in some cases eight, beam pulses. Primary beam intensity information, as determined by a secondary emission monitor (SEM) in the PW beamline, was recorded for each beam pulse. The scintillator paddles in the MERL were approximately 4 feet above the ground.

RESULTS AND DISCUSSION

1. Muon Fluence

Muon fluence based on singles counting rates and normalized to 10^{12} incident protons, are given in Tables 2-4. Lateral distance at each location is referenced to the point at which an extension of the PW secondary beamline would intersect the location; negative distances are to the East, positive distances to the West of the intersection point. Also shown are ratios of coincidence-to-single rates. For a parallel beam of muons striking the scintillator paddles perpendicular to the surface, the singles and coincidence rates should be equal. However, the muons produced along the PW beamline (which is well underground), will tend to strike the aboveground MERL paddles over a range of angles relative to the normal to the surface. They will therefore be detected with reduced coincidence efficiency.[2] From the observed coincidence-to-singles ratios of 0.5-0.67 at the peaks of the fluence distributions, results based on singles counting rates may be systematically high, but by a factor of two at most.

Neither the PC nor the PE beamlines operated with proton intensities greater than about 1% of PW values during the course of these measurements, and so they contributed negligible muon flux. For the observations at location 3, however, both NE and NW beams were running. While this could lead to some error in the results at the three most-Westerly positions (Table 4) since normalization was to the PW SEM, it is not thought likely as NE and NW intensities were only 10% of that for PW.

A characteristic of the observed lateral muon-fluence distributions, is the existence of two peaks (Tables 2-4). To investigate the origin of this structure the Monte Carlo program HALO[3] was used to trace the transport of muons produced in the decay of pion and kaon parents. The PW beamline components were entered from a previously written computer file.[4] The E615 mass-selection magnet with a Be hadron filter filling the gap, and the analyzing magnet ROSIE were included in the beam transport model with field maps approximated by BM109 maps scaled to larger dimensions. Downstream of PW8 the land surface was modeled out to the site-boundary (location 3, Table 1) using known values of surface elevations. Muon energy-loss through all materials including soil was taken into account in following the muon paths.

The lateral distribution of muon fluence at location 1, predicted by HALO for pion parents, is shown in Fig. 1 at several distances (6-19 feet) above beamline elevation (733 feet). As seen, the double-peaked nature of the structure disappears between 8 and 11 feet, and at a height of 19 feet, which is the approximate vertical position of the MERL paddles at this location, only a single peak is predicted. Even so, the absolute value of the observed muon fluence in the East peak compares favorably with that calculated. Inclusion of kaons in the calculation increases the absolute numbers by about 25% but, as seen in Fig. 1, does not alter the shape of the distribution. The contribution from "wrong sign" parents is negligibly small.

The HALO results at locations 2 and 3 for muons from both pion and kaon decay are compared to the observations in Fig. 2. At location 2 (Eola Road) the agreement is quite good in shape, although the predicted structure is shifted 25 feet toward the East relative to the measurements; the calculations are about twice as large as the observations in magnitude. At the site-boundary location the calculated fluence is substantially lower than that measured over most of the lateral range. Furthermore, at this location HALO predicts that the muon fluence is an order of magnitude larger at a height of 200-250 feet than at ground levels.

2. Muon Dose-Equivalent

Muon dose-equivalents are given in Tables 2-4 and plotted in Fig. 3 for 10^{18} incident protons. A fluence-to-dose equivalent conversion factor of 2.81×10^{4} muons-cm^{-2}-$mrem^{-1}$ (the value appropriate for muons outside at a thick shield[5]) was used. Although 10^{18} protons is the yearly value that past-experience has indicated is typical for a target contributing significant muon fluence, only about 2.5×10^{17} protons were in fact delivered to the PW target during the 800-GeV portion of the 1984 running period.

Traditionally the site-boundary dose-rate from Fermilab operation is primarily due to muons.[6] The present results suggest an expected maximum of 2.8 mrem for 10^{18} protons targetted in PW. The actual muon dose at the site-boundary for the past year was a factor of 4 lower (about 0.7 mrem) during 800 GeV operation. Both values are considerably less than either the DOE 500 mrem yearly limit to an individual in the general population, or the more stringent 170 mrem-$year^{-1}$ limit to an unmonitored member of the public. They are, furthermore, lower than the 10 mrem yearly limit set by the Fermilab Director. On the other hand, the value of 2.8 mrem is significantly higher than the value of $\sim$ 0.2 mrem for 10^{18} protons reported by Cossairt[1] at 350 GeV.

We acknowledge with many thanks the aid that Anthony Malensek gave us in the use and understanding of the HALO program. We thank Don Cossairt for a critical reading of this report.

REFERENCES

1. Cossairt, J. D., 1981., "Recent Muon Dose-Equivalent Measurements at Fermilab," TM-1061; Ibid., 1983, Health Phys. 45, 657.

2. Not every muon incident on one paddle will be detected by both.

3. Iselin, Ch., 1974., "HALO, A Computer Program to Calculate Muon Halo," CERN 74-17, Geneva.

4. We thank Jon Hawkins for the use of this file.

5. Van Ginneken, A., 1975., "Penetration of Prompt and Decay Muon Components of Hadronic Cascades Through Thick Shields," TM-630; Radiation Guide, 1983, Fermilab, 4th Edition.

6. Baker, S. I., 1984, "Environmental Monitoring Report for 1983," Fermilab 84/83, 1104.100, UC-41.

TABLE 1. Locations at which measurements were made.

Location	Longitudinal Distance from PW6 (approx.) (feet)	Surface Elevation (feet)	Description of Survey Location
1	1016	748	Just North of road in back of PW8 in parking lot near E326 portakamp. Survey was taken parallel to base of PW berm.
2	2616	742	Along Eola Road (which is normal to extension of PW beamline).
3	10616	738	Along Rt. 38 (Roosevelt Road) just West of intersection with Town Road. This is site-boundary survey location.

TABLE 2. Results of Measurements at Location 1. The errors are based on counting statistics only.

	For 10^{12} incident protons		For 10^{18} incident protons
Distance[a] (feet)	Singles (muons-cm^{-2})	$\frac{\text{Coincidences}}{\text{Singles}}$	Dose-Equivalent (mrem)
-29	4.10 ± .02	0.598 ± .006	146.0 ± .7
-27	6.39 ± .02	0.614 ± .004	227.6 ± .7
-21	22.30 ± .05	0.658 ± .003	794 ± 2
-15.5	39.48 ± .08	0.663 ± .002	1406 ± 3
-11	28.69 ± .06	0.665 ± .002	1022 ± 2
-5	20.65 ± .04	0.624 ± .002	735 ± 1
0.5	21.32 ± .04	0.594 ± .003	759 ± 1
6	33.40 ± .07	0.604 ± .002	1189 ± 3
11	35.71 ± .07	0.607 ± .002	1272 ± 3
17	24.35 ± .05	0.594 ± .002	867 ± 2
23	3.74 ± .02	0.511 ± .005	133.2 ± .7
30	1.05 ± .01	0.47 ± .01	37.4 ± .4
36	0.40 ± .01	0.40 ± .02	14.3 ± .4

[a]Distance is measured from the point at which an extension to the PW beamline would intersect the location. Distances to the West are postive (+), to the East are negative (-).

TABLE 3. Results of Measurements at Location 2. The errors are based on counting statistics only.

Distance[a] (feet)	For 10^{12} incident protons Singles (muons-cm^{-2})	Coincidences / singles	For 10^{18} incident protons Dose-Equivalent (mrem)
-132	0.066 ± .006	0.33 ± .04	2.4 ± .2
-102	0.130 ± .006	0.47 ± .03	4.6 ± .2
-72	0.497 ± .009	0.59 ± .02	17.7 ± .3
-57	1.15 ± .01	0.57 ± .01	41.0 ± .4
-42	1.45 ± .01	0.60 ± .01	51.6 ± .4
-12	0.603 ± .009	0.54 ± .01	21.5 ± .3
18	1.54 ± .02	0.59 ± .01	54.8 ± .7
48	1.05 ± .01	0.64 ± .01	37.4 ± .4
77	0.213 ± .008	0.61 ± .03	7.6 ± .3
101	0.058 ± .008	0.37 ± .07	2.1 ± .3
125	0.021 ± .006	0.32 ± .12	0.8 ± .2

[a]See comment in Table 2.

TABLE 4. Results of Measurements at Location 3. The errors are based on counting statistics only.

Distance[a] (feet)	For 10^{12} incident protons: Singles (muons-cm^{-2})	For 10^{12} incident protons: Coincidences / singles	For 10^{18} incident protons: Dose-Equivalent (mrem)
-705	0.011 ± .006	--	0.4 ± .2
-605	0.011 ± .006	0.2 ± .2	0.4 ± .2
-505	0.014 ± .005	0.5 ± .2	0.5 ± .2
-405	0.033 ± .005	0.46 ± .09	1.2 ± .2
-305	0.06 ± .01	0.42 ± .08	2.1 ± .4
-205	0.047 ± .005	0.55 ± .07	1.7 ± .2
-105	0.046 ± .006	0.48 ± .07	1.6 ± .2
-5	0.08 ± .01	0.51 ± .09	2.8 ± .5
95	0.075 ± .005	0.55 ± .04	2.7 ± .2
195	0.073 ± .006	0.46 ± .05	2.6 ± .2
295	0.046 ± .006	0.42 ± .07	1.6 ± .2
395	0.045 ± .005	0.57 ± .08	1.6 ± .2
495	0.035 ± .007	0.6 ± .1	1.2 ± .3
595	0.009 ± .007	0.2 ± .2	0.3 ± .2

[a]See comment in Table 2.

FIGURE CAPTIONS

1. The lateral distribution of muon fluence per 10^{12} incident protons at location 1 as a function of vertical distance above beamline elevation. The histograms are HALO calculations at 250-GeV with negative pion parents, except as noted.

2. The lateral distribution of muon fluence per 10^{12} incident protons at locations 2 and 3. The histograms are HALO calculations at 250-GeV for positive pions and kaons (E615 was in this mode of operation during the time of these measurements) at the height above beamline elevation of the MERL paddles.

3. The measured lateral distribution of muon dose-equivalent for 10^{18} protons at the three locations. The dashed lines are to guide the eye.

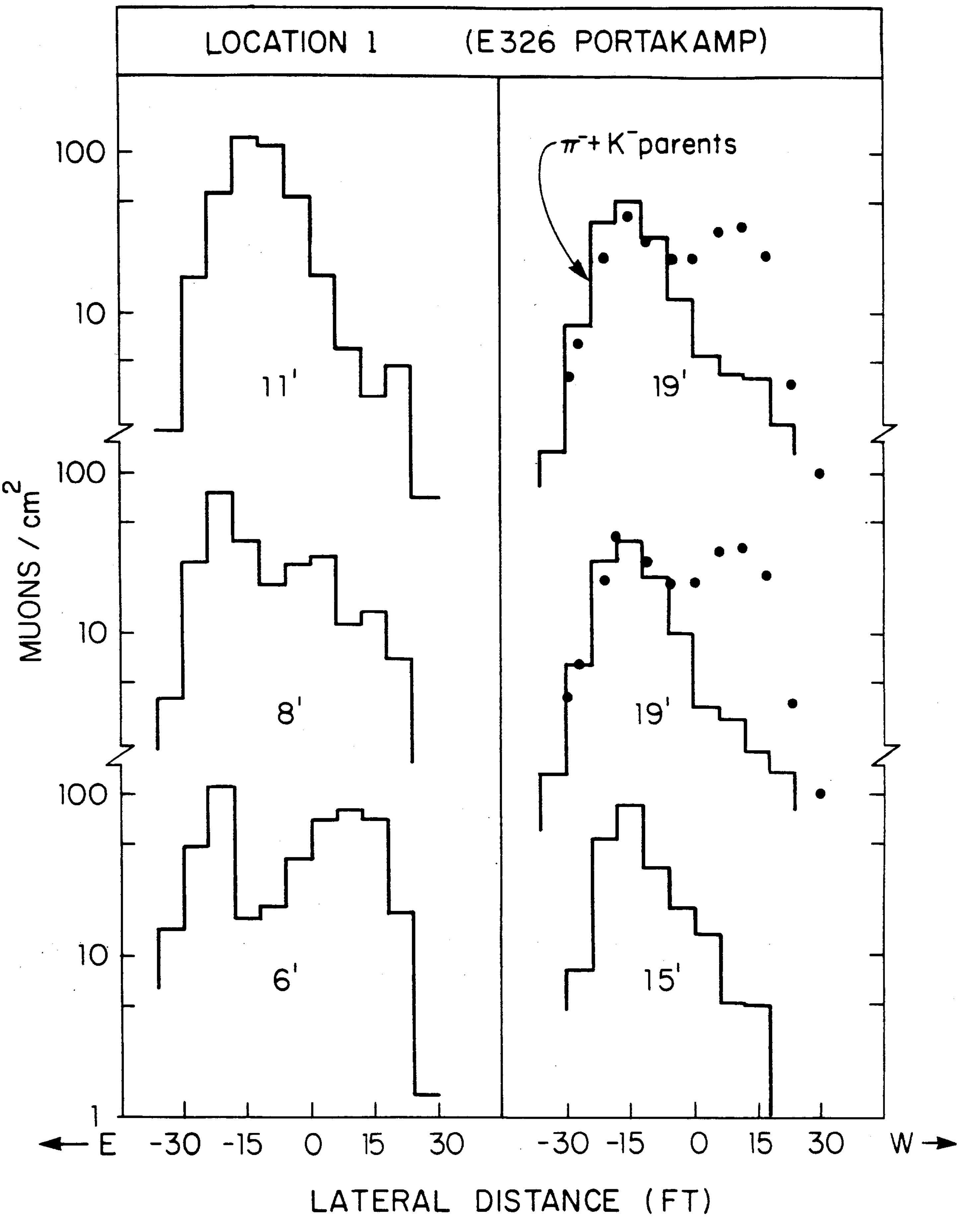
LOCATION 1 (E326 PORTAKAMP)
$\pi^- + K^-$ parents
MUONS / cm^2
100
10
1
11'
8'
6'
19'
19'
15'
← E
W →
-30 -15 0 15 30
LATERAL DISTANCE (FT)

Fig. 1

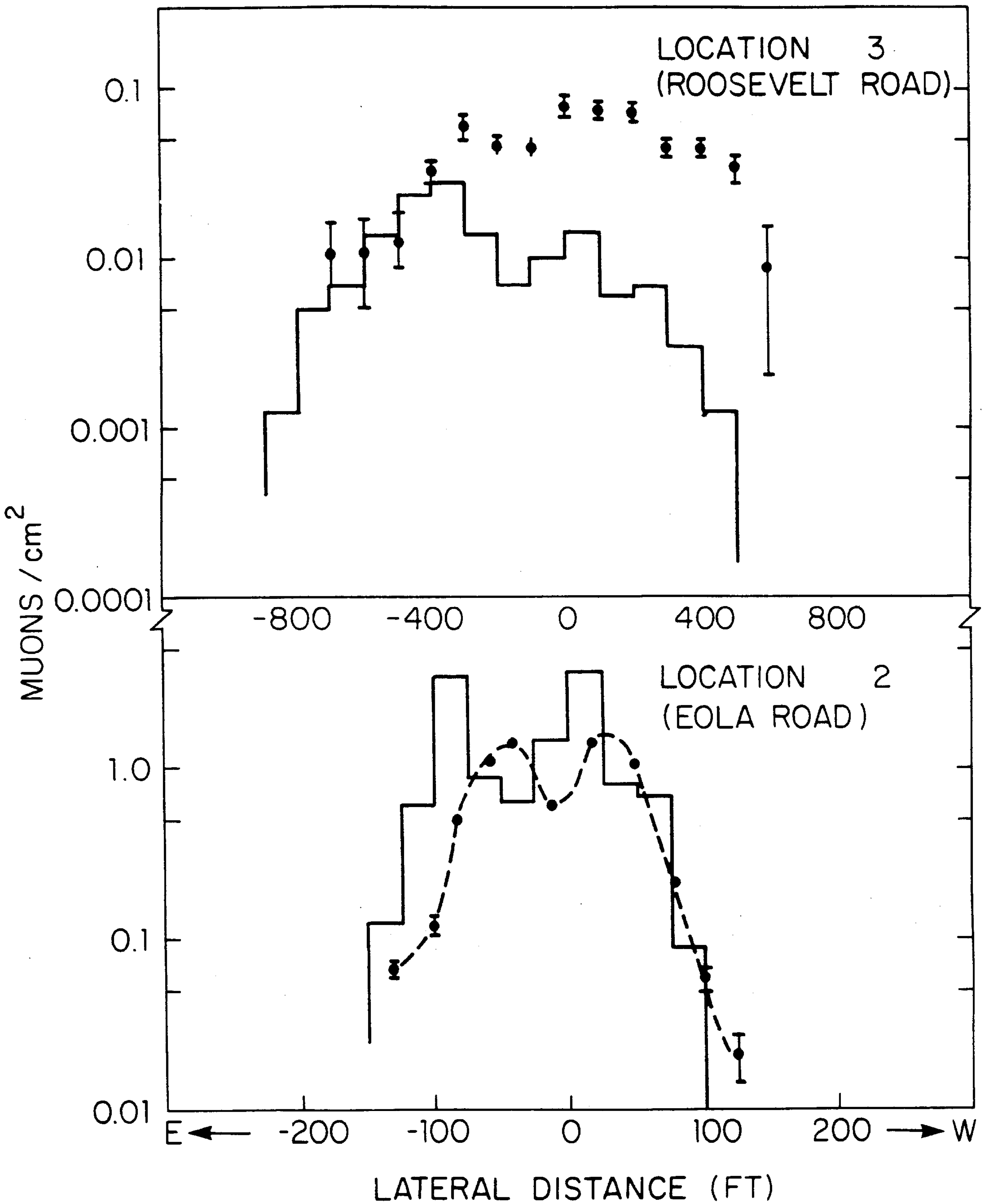
LOCATION 3
(ROOSEVELT ROAD)
0.1
0.01
0.001
0.0001
-800
-400
0
400
800
MUONS / cm²
LOCATION 2
(EOLA ROAD)
1.0
0.1
0.01
E
-200
-100
0
100
200
W
LATERAL DISTANCE (FT)

Fig. 2

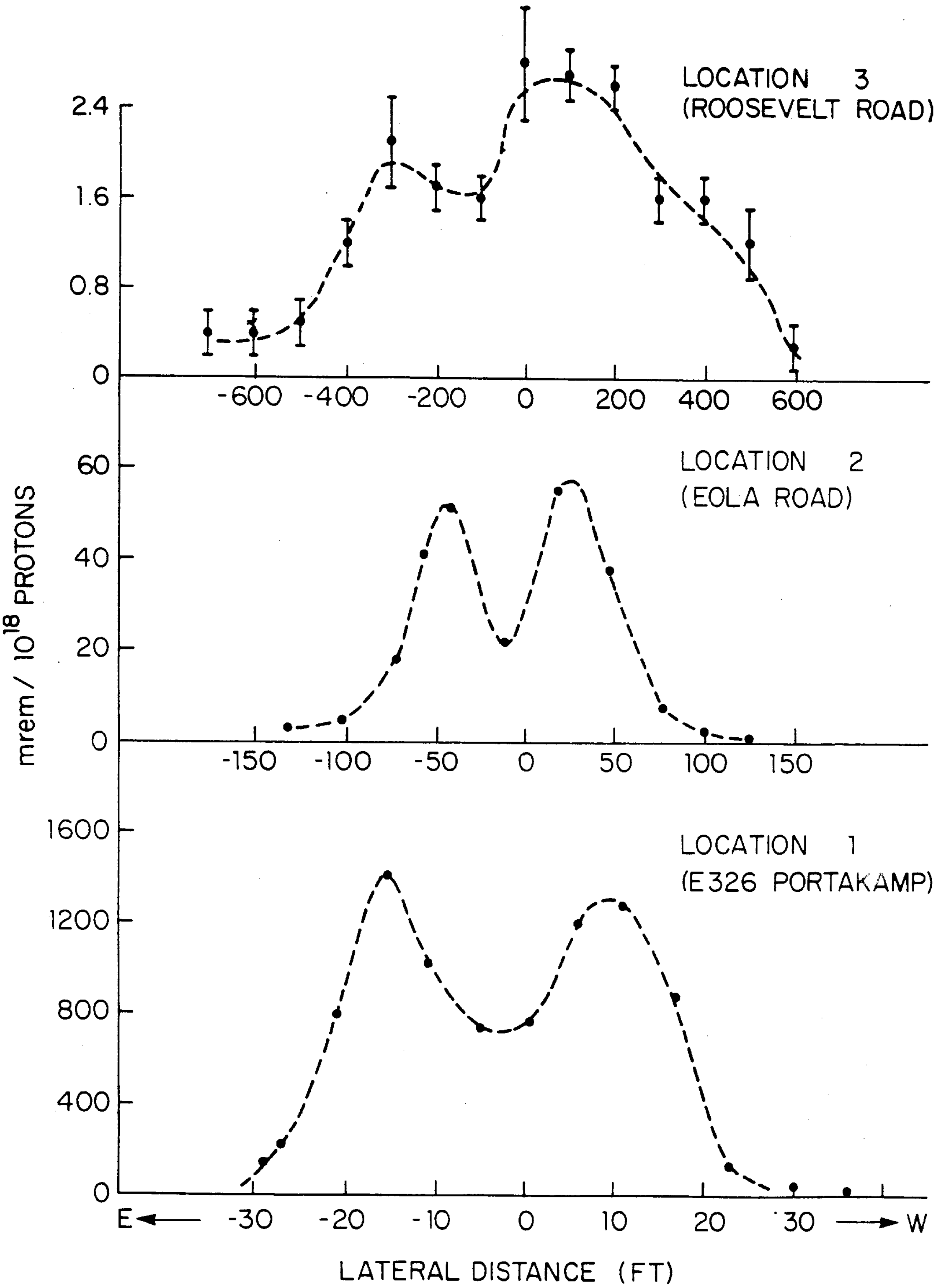
LOCATION 3
(ROOSEVELT ROAD)
LOCATION 2
(EOLA ROAD)
LOCATION 1
(E326 PORTAKAMP)
mrem / 10^18 PROTONS
2.4
1.6
0.8
0
-600
-400
-200
0
200
400
600
60
40
20
0
-150
-100
-50
0
50
100
150
1600
1200
800
400
0
E
-30
-20
-10
0
10
20
30
W
LATERAL DISTANCE (FT)

Fig. 3